CAN FIREBALL OR FIRECONE MODELS EXPLAIN GAMMA RAY BURSTS?

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ABSTRACT

The observed afterglows of gamma ray bursts (GRBs), in particular that of GRB 970228 six months later, seem to rule out relativistic fireballs and relativistic firecones driven by merger or accretion induced collapse of compact stellar objects in galaxies as the origin of GRBs. GRBs can be produced by superluminal jets from such events.

1. INTRODUCTION

The isotropy of the positions of gamma ray bursts (GRBs) in the sky and their brightness distribution have provided the first strong indication that they are at cosmological distances (Meegan et al 1992; Fishman and Meegan 1995 and references therein). The recent discovery of an extended faint optical source coincident with the optical transient of GRB 970228 (Groot et al. 1997; van Paradijs et al. 1997; Sahu et al. 1997) and, in particular, the detection of absorption and emission line systems at redshift z=0.835 (Metzger et al. 1997a,b) in the spectrum of the optical counterpart of GRB 970508, which may arise from a host galaxy (see e.g. Pedersen et al 1997), have provided further evidence that GRBs take place in distant galaxies. The peak luminosity of GRB 970508 in the 0.04-2.0 MeV range exceeded $10^{51} d\Omega\ erg\ s^{-1}$ (assuming $\Omega \approx 0.2$, $\Lambda = 0$ and $H_0 \approx 70\ km\ Mpc\ s^{-1}$), where $d\Omega$ is the solid angle into which the emitted radiation was beamed. Such γ-ray luminosities and their short time variability strongly suggest that GRBs are produced by mergers and/or accretion induced collapse (AIC) of compact stellar objects (Blinnikov et al. 1984; Paczynski 1986; Goodman, Dar and Nussinov 1987), the only known sources which can release such enormous energies in a very short time. Then the

gamma rays must be highly collimated and their radius of emission must be large enough in order to avoid self opaqueness due to $\gamma\gamma \to e^+e^-$ pair production. A sufficient, and probably necessary, condition for this to occur is that they are emitted by highly relativistic outflows with bulk Lorentz factors, $\Gamma = 1/\sqrt{1-\beta^2} \gg 100$. Additional support for their emission from highly relativistic flows is provided by their non thermal energy spectrum. Consequently relativistic fireballs (Cavallo and Rees 1976; Paczynski 1986; Goodman 1986) and relativistic jets (e.g., Shaviv and Dar 1995; Dar 1997) were proposed as the producers of GRBs. The observed radiation may be produced by self interactions within the flow (e.g., Paczynski and Xu 1994; Rees and Meszaros 1994) or by interactions with external matter (e.g. Rees and Meszaros 1992; Meszaros and Rees 1993) or with external radiation (e.g., Shemi 1993; Shaviv and Dar 1995; 1996).

Following the discovery of the afterglow of GRBs 970228 various authors have concluded that it supports the fireball model of GRBs (e.g., Katz et al. 1997; Waxman 1997a,b; Wijers et al. 1997; Reichart 1997; Vietri 1997; Rhoads 1997; Sari 1997a; Tavani 1997; Sahu et al 1997a). However, here we show that the detailed observations of the afterglows of GRBs 970111, 970228, 970402, 970508, 970616, 970828, 971214, and in particular that of 970228 six months later (Fruchter et al, 1997), support neither the simple relativistic fireball model (e.g., Meszaros and Rees 1997), nor simple relativistic firecone (conical ejecta) models. However, if the relativistic ejecta in merger/AIC of compact stellar objects is collimated into magnetically confined narrow jets, the major problems of the fireball and firecones models can be avoided and the general properties of GRBs and their afterglows can be explained quite naturally.

2. FAILURES OF SIMPLE FIREBALLS

2.1. Energy Crisis

The spherical blast wave models assume (e.g., Meszaros and Rees 1997; Wijers et al 1997) that the ultrarelativistic spherical shell which expands with a Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$ drives a collisionless (magnetic) shock into the surrounding interstellar medium. They also assume that the collisionless shock which propagates in the ISM with a Lorentz factor $\gamma_s = \sqrt{2}\gamma$ accelerates it and heats it up to a temperature $T \approx \gamma m_p c^2$ (in its rest frame). Energy-momentum conservation in the ultrarelativistic limit, which reads $d[(M + nm_p(4\pi/3)r^3)\gamma^i] \approx 0$ with $i = 2$, then implies that the bulk Lorentz factor of the decelerating debris (mass M) and swept up ISM (ambient density n) decreases for large r like $\gamma(r) \sim \gamma(r_0)(r/r_0)^{-3/2}$. In fact, the assumption that a highly relativistic collisionless shock heats up the ISM to a temperature $T_p \approx \gamma m_p c^2$ in its rest frame, has never been

substantiated by self consistent magnetodynamic calculations nor by direct observations of radiation from decelerating superluminal jets. For $T_p < m_p c^2$ (or fast cooling) one has $i = 1$ and $\gamma \sim r^{-3}$. It is further assumed that superthermal electrons, with a power-law spectrum, $dn_e/dE' \sim E'^{-p}$ and $p \approx 2.5$, in the rest frame of the shocked ISM emit synchrotron radiation with a power-law spectrum $h\nu dn/d\nu' \sim \nu'^{-(p-1)/2}$ (or $\sim \nu'^{-p/2}$ for fast cooling) from an assumed equipartition internal magnetic field. Photons which are emitted with a frequency ν' in the rest frame of the shocked material and at an angle $cos\theta'$ relative to its bulk motion, are viewed in the lab frame at a frequency ν and at an angle θ which satisfy, respectively, (e.g. , Rybicki and Lightman 1979)

$$\nu = \gamma(1+\beta cos\theta')\nu' \ ; \quad tan\theta = sin\theta'/\gamma(\beta + cos\theta'). \tag{1}$$

If $\gamma >> 1$ and if the photons are emitted isotropically in the rest frame of the shocked material with differential intensity $I_\nu = h\nu' dn/d\nu'$, then in the lab frame they have an angular and spectral distribution

$$\frac{dI_\nu}{dcos\theta} = \frac{4\gamma^3}{(1+\gamma^2\theta^2)^3} I_{\nu'=\nu(1+\gamma^2\theta^2)/2\gamma}. \tag{2}$$

Thus, a distant observer sees essentially only photons emitted in his direction from radius vectors r with angles $\theta \leq 1/\gamma$ relative to his line of sight (l.o.s.) to the explosion center ($r = 0$). If the emission from the shocked ISM between the expanding debris and the shock front is uniform, then the photon arrival times are

$$t \approx \frac{r}{\alpha_i c[\gamma(r)]^2} - \frac{r'}{2\alpha_i c[\gamma(r')]^2} + \frac{r\theta^2}{2c}, \tag{3}$$

where $r' \leq r$ is the initial distance of the shocked material from the explosion point and $\alpha_i = 2(6/i+1) = 14, 8$ for $i = 1, 2$, respectively. If the photons are emitted mainly from a thin shell behind the shock front then $r' \approx r$ and

$$t \approx \frac{r}{2\alpha_i c[\gamma(r)]^2} + \frac{r\theta^2}{2c} \ . \tag{4}$$

Photons which are emitted from the shock front at $\theta = 0$ reach the observer at a time

$$t = r/2\alpha_i c\gamma^2 \ . \tag{5}$$

Neglecting redshift effects, the differential luminosity seen by the observer at time t is obtained by integrating eq. 2 over $r' \leq r$, r and θ, subject to eq. 3 (thick shell) or eq. 2 (thin shell). Because the angular delay dominates eqs. 3 and 4, the emissivity is weighted in the integration by $2\pi\theta d\theta$, the integrand peaks at $\theta^2 = 1/(6-i+p)\gamma^2$. Substituting

that into eq. 4, we find that for thin adiabatic shells ($i = 2$) most of the high frequency photons which arrive at time t come from a ring around the l.o.s. whose distance R and Lorentz factor $\gamma(R)$ satisfy eq. 5 with $\alpha_2 \approx 3.6$ and $R = 0.77 R_{max}$, while for thin radiative shells ($i = 1$) we find $\alpha_1 \approx 4.9$ and $R \approx 0.84 R_{max}$. Very similar results were obtained by Panaitescu and Meszaros (1997) from exact numerical integrations.

The relativistic expansion lasts until $\gamma(r) \approx 2$, i.e., $t \approx r/8\alpha_i c$. Since the energy of the swept up material is $\approx (4\pi/3) r^3 n \gamma^i m_p c^2$, the explosion energy must satisfy

$$E \geq 2.7 \times 10^{54} n(\alpha_i/[1+z])^3 i^2 t_y^3 \; erg, \tag{6}$$

where n is the mean density of the swept up ISM in cm^{-3}, t_y is the observer time in years, and z is the redshift of the host galaxy where the explosion took place. (The factor $i^2 = 4$ for the thick shell/adiabatic expansion case follows from the assumption that the proton and electron temperatures are both $\sim \gamma m_p c^2$). The shape, angular size ($0.8''$) and magnitude ($V = 25.7 \pm 0.15$) of the host nebula of GRB 970228 that were measured by HST between Sep. 4.65 and 4.76 UT ($t_y \approx 0.52$) suggest that it is a galaxy with a redshift $z < 1$. For $z = 1$, a standard ISM density $n \sim 1 \; cm^{-3}$, $i = 1$ and $\alpha_1 \approx 4$ calculated by Panaitescu and Meszaros (1997) for a thin/radiative shell, eq. 6 yields $E \geq 3 \times 10^{54} \; erg$. For a thick/adiabatic shell ($i = 2$) and $\alpha_2 \approx 2$ eq. 6 yields $E \geq 1.5 \times 10^{54} \; erg$. Such energies, are comparable to the total energy-release in mergers/AIC of compact stellar objects, which is usually less than $\sim M_\odot c^2 \approx 1.8 \times 10^{54} erg$. Such kinetic energies, however, are larger by orders of magnitude than the maximal plausible kinetic energies of spherical explosions produced by such events. This is because a large fraction of the released energy is radiated in gravitational waves, and neutrino emission is inefficient in driving spherical explosions in gravitational collapse of compact objects. Typically, in core collapse supernovae explosions, the kinetic energies of the debris is about $\sim 1\%$ of the total gravitational binding energy release. NS merger/AIC is not expected to convert a larger fraction of the gravitational binding energy release into kinetic energy of a spherical explosion. First, a large fraction of the binding energy is radiated away by gravitational waves emission, which is relatively unimportant in Type II supernova explosions. Second, neutrino deposition of energy and momentum in the ejecta is less efficient in NS mergers, because it lasts only for milliseconds and because neutrino trapping and gravitational redshift of neutrino energy are stronger than in core collapse supernovae. Indeed, detailed numerical calculations of spherical explosions driven by neutrinos in NS mergers (e.g., Janka and Ruffert 1996; Ruffert et al 1997) produce very small explosion energies. Although the numerical calculations still are far from being full general relativistic three dimensional calculations, let alone their inability to reproduce consistently supernova explosions, probably, they do indicate the correct order of magnitude of the kinetic energy in spherical explosions driven by NS merger or AIC of white dwarfs and NS.

The fluence of GRB 970508 was $\geq 10^{52} erg$ in the 0.04-2.0 MeV alone, assuming isotropic emission. If hundred times brighter GRBs, like GRB 970616, have redshifts similar to that of GRB 970508, their fluences must be $\sim 10^{54}$ erg for isotropic emission. It also cannot be supplied by mergers/AIC of compact stellar objects.

2.2. Absence of Simple Scaling

Relativistic blast wave models predict that GRB afterglows are scaled by powers of their basic parameters: total energy E, initial Lorentz factor Γ, surrounding gas density n, and distance D. However, GRBs 970111, 970228, 970402, 970508, 970616, 970828 and 971214 exhibited unscaled behavior and very different spectral properties (for the X-ray observations see Costa et al. 1997; Piro et al., 1997; Castro-Tirado et al 1977; Feroci et al 1977; Heise et al. 1997; Odewahn 1997; Frontera et al 1997; for optical observations see the compilation in Reichart 1997; Sahu et al 1997b; Pedersen et al 1997; and Halpern et al. 1997; A. Diercks et al. 1997; for radio observations see Frail et al 1997b and references therein). For instance, GRB 970111 and GRB 970828 had γ-ray fluences ~ 25 times larger than GRB 970228 but their afterglow were not detected in X-rays, in the optical band and in the radio band (e.g., Groot et al. 1997b; Frontera et al. 1997). The upper bound on the optical peak response of GRB 970828 was $\sim 10^2,\ 10^3$ smaller than that of GRB 970228 and GRB 970508, respectively (Groot et al 1997b). GRB 970508 was 6 times weaker in γ-rays than GRB 970228 (Kouveliotou et al 1997, Hurley et al 1977) but 6 times brighter in the optical band (see, e.g., Sahu et al 1977b and references therein). Such spectral variability is observed in the afterglows of gamma ray flares from extragalactic relativistic jets of blazars and also in flares from galactic relativistic jets of microquasars (galactic superluminal sources) such as GRS 1915+105 (Mirabel and Rodriguez 1994) and GRO J1655-40 (Tingay et al. 1995).

2.3. Firecone Rescue?

The radiated energy of GRB 970228 during the afterglow in the 2-10 keV window alone was about 40% of the energy in the gamma burst itself in the 40-700 keV band (Costa et al. 1997). For such a fast cooling, energy-momentum conservation requires $\gamma \sim r^{-3}$, instead of $\gamma \sim r^{-3/2}$ for a slow cooling, which was used to derive the $\sim t^{-3(p-1)/4}$ fading of the X-ray and optical afterglows (Wijers et al. 1997) of GRBs. Also the relation between observer time, emissiom radius and Lorentz factor which was used is not correct. Thus, the only successful prediction of the afterglow model is also in doubt. Moreover, the duration (in

months) of the initial power-law fading of the afterglow (thin radiative shell, $i = 1$, $\alpha_1 \approx 4$) which last until $\gamma(R) \approx 2$ is

$$t_m \approx 1.85 E_{52}^{1/3}[(1+z)/i^{2/3}\alpha_i n^{1/3}]\ months, \tag{7}$$

where $E_K = 10^{52}E_{52}\ erg$ and n in cm^{-3}. This short cooling time is already in conflict with the observed $\sim t^{-1.1}$ fading of the afterglow of GRB 970228 over 6 months (Fruchter et al. 1997) if $[E_{52}/n]^{-1/3} \leq 1$, both for thin/radiative and thick/adiabatic shells. Note that GRBs 970228 and 970508 appear within the optical luminous part of the faint host galaxy (Sahu et al. 1997, Fruchter 1997, Metzger et al 1997, Djorgovski et al 1997) where one expects $n \sim 1$. Conical fireballs ("firecones") with opening angles $\theta_c > 1/\Gamma$ and solid angles smaller by $\theta_c^2/4$, can reduce the estimated total energy in γ-rays and X-rays by a factor $\sim \theta_c^2/4$. As long as $\theta_c > 1/\gamma$, fireballs and firecones look alike for observer near the axis of the firecone. But, when $\gamma\theta_c < 1$, the beaming efficiency decreases by $\gamma^2\theta_c^2$ and the $\sim t^{-1.1}$ fading of the optical afterglow is accelerated by a factor $\gamma^2 \sim t^{-6/(6+i)} = t^{-3/4}$, for thick/adiabatic conical shell. Such a change has not been observed yet in the afterglow of GRB 970228, implying that after six months $\gamma\theta_c > 2$. Therefor, firecones cannot solve (by additional factors < 4, $4^{1/3}$ on the r.h.s. of eqs. 6 and 7 , respectively) the energy crisis or explain the uniform power law fading of GRB 970228 for over six months. It can be shown easily that the crisis is larger for observers with larger viewing angles with respect to the firecone axis.

3. Short Time Variability

Even if the energy crisis in GRBs and the non-universality of their afterglows could have been avoided by assuming firecones, i.e. conical shells instead of relativisticly expanding spherical shells, neither firecones nor fireballs can explain subsecond variability in GRBs that last for tens or hundreds of seconds. First, a variable central engine must be fine tuned to arrange for shells to collide only after a distance where the produced γ-rays are not reabsorbed, which is larger by more than 10 orders of magnitude than the size of the central engine (Shaviv, 1996). Second, even with fine tuning of the central engine, the transverse size of the emitting area whose radiation is beamed towards the observer, $r\theta \leq r/\Gamma$ where $\Gamma \approx \gamma(0)$, implies variability on time scales (e.g., Shaviv 1996; Fenimore 1996)

$$\Delta t \sim r\theta^2/2c \approx r/2c\Gamma^2 \sim T_{GRB}, \tag{8}$$

i.e., comparable to the total duration of the GRB. It is in conflict with the observed short time variability of GRBs. Even GRBs that last more than 100 s, show a variability on subsecond time scales, (e.g., Fishman and Meegan 1995). Local instabilities are not efficient enough in producing high intensity pulses.

3.1. Extended GeV Emission

The initial Lorentz factor of a relativisticly expanding fireball, which sweeps up ambient matter, decays rather fastly ($t \sim T_{GRB}$) as its energy is shared by the swept up matter. It cannot explain emission of multi GeV γ-rays, which is extended over hours (in the observer frame) with an energy fluence similar to that in the keV/MeV GRB, as observed in GRB 910503 (Dingus et al. 1994) and in GRB 940217 (Hurley et al. 1994). Note in particular that inverse Compton scattering of GRB photons or external photons by the decelerating debris is not efficient enough in producing the observed extended emission of GeV photons. Also it cannot explain MeV γ-ray emission that extends over 2 days, which, perhaps, was the case if the cluster of four GRBs (Meegan et al. 1996; Connaughton et al. 1997) were a single GRB.

4. GRBS FROM ACCRETION JETS

Highly collimated relativistic jets seem to be emitted by all astrophysical systems where mass is accreted at a high rate from a disk onto a central (rotating?) black hole. They are observed in galactic and extragalactic superluminal radio sources, like the galactic microquasars GRS 1915+105 (Mirabel and Rodriguez 1994) and GRO J1655-40 (Tingay et al. 1995) and in many extragalactic blazars where mass is accreted onto, respectively, stellar and supermassive rotating black holes. They produce γ-ray flares with afterglows in the X-ray, optical and radio bands which rise fastly and decline with time like a power-law and have a non-thermal power-law spectra and hardness which is correlated with intensity. Highly relativistic jets probably are ejected also in the violent merger/AIC death of close binary systems containing compact stellar objects. Such jets which are pointing in our direction can produce the cosmological GRBs and their afterglows (Dar 1997b,c). Jetting the ejecta in merger/AIC of compact stellar objects can solve the energy crisis of GRBs by reducing the total inferred energy release in GRBs by the beaming factor $f = \Delta\Omega/4\pi$, where $\Delta\Omega$ is the solid angle into which the emission is beamed. In fact, in order to match the observed GRB rate (e.g. Fishman and Meegan 1995) and the currently best estimates of the NS-NS merger rate in the Universe (e.g. Lipunov et al. 1997) solid angles $\Delta\Omega \sim 10^{-2}$ are required. Such solid angles are typical of superluminal jets from Blazars. The estimated rate of AIC of white dwarfs and neutron stars is much higher, ~ 1 per second in the Universe compared with ~ 1 per minute for NS-NS mergers. If GRBs are produced by accretion induced collapse of white dwarfs and neutron stars (e.g., Goodman et al 1987; Dar et al 1992), then $\Delta\Omega \sim 10^{-4}$.

The FeII and MgII absorption lines and OII emission lines at redshift z=0.835 in the

afterglow of GRB 970508 seems to indicate that GRBs are produced in dense stellar regions, e.g. star burst regions. Boosting of stellar light by superluminal jets from merger/AIC in dense stellar regions (with typical size $R \approx 10^{18} \times R_{18}\ cm$ and photon column density $N_\gamma = N_{23} \times 10^{23}\ cm^{-2}$) has been proposed by Shaviv and Dar (1995; 1997) as the origin of GRBs. It can explain quite naturally the fluence, typical energy, duration distribution, light curves, spectral evolution and afterglows of GRBs. Due to space limitation, here we only demonstrate that it solves the main difficulties of the fireball/firecone models: If the ejected jet (blobs) has an initial kinetic energy $E_k = E_{52} \times 10^{52}\ erg$, a Lorentz factor $\Gamma = \Gamma_3 \times 10^3$, and a cross section $S_j \approx \pi R_j^2 = \pi R_{j16}^2 \times 10^{32}\ cm^2$ which after initial expansion remains constant due to magnetic confinement, then:

(a) The photon fluence at a distance $D = D_{28} \times 10^{28}\ cm$ due to photo absorption/emission by partially ionized heavy atoms (Shaviv 1996) in the jet ($\sigma_a = \sigma_{18} \times 10^{-18}\ cm^2$) is

$$I_\gamma \approx \frac{\eta E_k \sigma_T N_\gamma}{\Gamma m_p c^2 D^2 \Delta\Omega} = 7 \times \frac{\eta_2 E_{52} \sigma_{18} N_{23}}{D_{28}^2 \Gamma_3 \Delta\Omega_2}\ \gamma\ cm^{-2}, \tag{9}$$

where $\eta = \eta_2 \times 10^{-2}$ is the fraction of heavy atoms in the jet (we assume a cosmic ray composition).

(b) The typical energy of the emitted (Lorentz boosted) photons and the energy fluence in the observer frame are, respectively,

$$E_\gamma \approx \frac{\Gamma_3^2 \epsilon_{eV}}{(1+z)}\ MeV, \tag{10}$$

where $\epsilon = \epsilon_{eV} \times eV$ is the typical energy of stellar photons, and

$$F_\gamma \approx I_\gamma E_\gamma \approx 10^{-5} \times \frac{\eta_2 E_{52} \sigma_{18} N_{23} \Gamma_3 \epsilon_{eV}}{(1+z) D_{28}^2 \Delta\Omega_2}\ erg\ cm^{-2}. \tag{11}$$

(c) The typical duration of GRBs and the duration of individual pulses from boosting starlight of bright stars are given, respectively, by

$$T_{GRB} \approx \frac{R}{c\Gamma^2} = 30 R_{18} \Gamma_3^{-2}\ s,\ and\ \ T_p \approx \frac{R_j}{c\Gamma^2} = 0.30 R_{j16} \Gamma_3^{-2}\ s. \tag{12}$$

The bimodality of the duration distribution og GRBs (e.g., Fishman and Meegan 1995) has a simple statistical origin (Shaviv and Dar 1997).

(d) Due to energy-momentum conservation, an ejected jet (blob) with a an initial kinetic energy E_k, bulk-motion Lorentz factor Γ and constant cross section S_j is decelerated by the swept up interstellar matter according to $\gamma = \Gamma/(1 + R/R_0)$, or $R = R_0(\Gamma/\gamma - 1)$, where R is its propagation distance in the interstellar medium and $R_0 = E_k/n m_p c^2 \Gamma S_j$. The

electrons in the ejecta and the swept up interstellar matter whose total mass increases like $M \sim 1/\gamma$ are accelerated by the jet to a power-law spectrum in the jet rest frame. They emit synchrotron radiation with a power-law spectrum $\nu' dn/d\nu' \sim \nu'^{-(p-1)/2}$ with intensity proportional to their number and to the magnetic energy density. For an observer within the beaming cone, this synchrotron emission is Lorentz boosted and collimated according to eq. 2, i.e., it is amplified by a factor $A \sim \gamma^{3+(p-1)/2}$. Thus, an observer within the beaming cone sees a synchrotron afterglow with intensity $I_\nu \sim AB^2 M(dt'/dt)$. Since $dt = dt'/2\gamma$ and $t = \int dR/2\gamma^{-2} = (R_0/6c\Gamma^2)[(\Gamma/\gamma)^{-3} - 1]$, one obtains for $p = 2.5 \pm 0.5$ that

$$I_\nu \sim \gamma^{3+(p-1)/2} \sim (t + t_0)^{-1.25\pm 0.08} \tag{13}$$

where $t_0 = R_0/6c\Gamma^2 \approx (E_{52}/n\Gamma_3^3 R_{j16}^2) \times 100\ s$. Initial expansion of the ejecta, changes in opacity within the jet and along the trajectory of the emitted radiation, and viewing angle effects due to the change in the beaming angle, can produce complex time and wavelength dependences of the afterglow in the initial phase. Moreover, absorption of optical photons, UV photons and X-rays by the interstellar gas and dust around the burst location depends strongly on energy. Gas Column densities $N_H \geq 10^{22}\ cm^{-2}$, which are also required by the detection of GeV emission from bright GRBs (see below), can explain why some GRBs afterglows which were detected in X rays were not detected also in the optical band. If this explanation for the suppression of optical afterglows of GRBs is correct, then X-ray afterglows of GRBs which are not accompanied by optical afterglows must show harder X-ray spectra than those of GRBs with optical afterglows. Such GRBs must also be accompanied by strong emission of GeV photons.

Inhomogeneous ISM and jet instabilities can modify the late time behavior of the afterglows. For instance, if the jet is deflected by a stellar or interstellar magnetic field, the afterglow may disappear suddenly from the field of view (collisions and deflection of jets on scales 10-100 pc were observed in AGN, e.g., Mantovani et al. 1997).

(e) The high column density of gas in star forming regions, $N_H = N_{23} \times 10^{23}\ cm^{-2}$, with $N_{23} \geq 1$, provides an efficient target for hadronic production of high energy photons via $pp \to \pi^0 X$ followed by the prompt $\pi^0 \to 2\gamma$ decay. A power-law proton spectrum produces a power-law photon spectrum with the same power index and efficiency (e.g., Dar 1997) $g\sigma_{in} N_H$ where $g = 10^{-1} \times g_1 = 0.195 exp[-3.84(p-2) + 1.220(p-2)^2]$ and $\sigma_{in} \approx 3 \times 10^{-26}\ cm^2$ is the pp inelastic cross section. Consequently, GRBs in star forming regions are accompanied by emission of a power-law spectrum of high energy photons with a total fluence

$$F(> 100\ MeV) \approx \frac{E_{52} g_1 N_{23}}{D_{28}^2 \Delta\Omega_2} \frac{3}{1+z} \times 10^{-6} erg\ cm^{-2}, \tag{14}$$

comparable to the GRB fluence in MeV γ rays. This is consistent with the detection of GeV photons by the EGRET instrument on board the Compton Gamma Ray Observatory

from a handful of bright bursts (see, e.g., Dingus 1995). Given the EGRET sensitivity and limited field of view, the detection rate implies that high energy emission may accompany most GRBs.

Finally, significant hadronic production of gamma rays with energy $\sim 18\ GeV$, as observed in GRB 940217, requires incident proton energies ~ 6 times larger, i.e., that $\gamma > 115$. Consequently, the effective duration of emission of such photons is

$$t(E_\gamma < 18GeV) \approx \frac{R_0}{6c\gamma^2} \approx \frac{E_{52}}{n\Gamma_3 R_{j16}^2} \times 2.5h, \tag{15}$$

which is consistent with the EGRET/CGRO observations (Hurley 1994).

5. CONCLUSIONS

The observed properties of GRBs and their afterglows, in particular that of GRB 970228 six months later, seem to rule out relativistic fireballs and firecones powered by mergers/AIC of compact stellar objects within galaxies as the origin of GRBs. In spite of their flexibility and multitude of free parameters, the simple fireball and firecone models of GRBs appear not to be able to explain the total energy of GRBs, nor to explain the enormous diversity of GRBs, their short time scale (subsecond) variability, their spectral evolution, the delayed emission of MeV and GeV γ-rays in some GRBs, and the spectral versatility of GRB afterglows. In order to solve these problems, the single relativistic spherical shell which expands into a uniform medium must be replaced by a fine tuned series of asymmetric shells (conical ejecta) which expand into a nonuniform medium (e.g., Meszaros et al 1997). This adds many new parameters to the "fireball" model which can be adjusted to fit any GRB and rescue the model. However, this increased flexibility through a multitude of new adjustable parameters makes the modified relativistic fireball/firecone models too flexible, without predictive power and unfalsifyable, and therefor scientifically unacceptable. However, if the relativistic ejecta in merger/AIC of compact stellar objects is collimated into highly relativistic jets, most of the problems of the spherical fireball models can be avoided and the general properties of GRBs and their afterglows can be explained quite naturally using the observed properties of superluminal jets from blazars and microquasars. In particular, if GRBs are produced by highly relativistic jets which are pointing in our direction they should show superluminal motions with speeds $v \leq \Gamma c$. Such supeluminal motions may be detected in long term (months) VLBI observations of radio afterglows of GRBs (see, e.g., Taylor et al. 1997).

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